Autonomous Robots 11, 39–47, 2001

An Advanced Telereflexive Tactical Response Robot

H.R. EVERETT, G.A. GILBREATH AND D.A. CICCIMARO
SPAWAR Systems Center*, San Diego, Code D371, 53406 Woodward Road, San Diego, CA 92152-7383
everett@spawar.navy.mil

Abstract. ROBART III is intended as an advanced demonstration platform for non-lethal tactical response, extending the concepts of reflexive teleoperation into the realm of coordinated weapons control (i.e., sensor-aided control of mobility, camera, and weapon functions) in law enforcement and urban warfare scenarios. A rich mix of ultrasonic and optical proximity and range sensors facilitates remote operation in unstructured and unexplored buildings with minimal operator oversight. Supervised autonomous navigation and mapping of interior spaces is significantly enhanced by an innovative algorithm which exploits the fact that the majority of man-made structures are characterized by (but not limited to) parallel and orthogonal walls. This paper presents a brief overview of the advanced telereflexive man-machine interface and its associated "human-centered mapping" strategy.

Keywords: robotics, teleoperated, telereflexive, non-lethal response, world modeling, human-centered mapping, robotic sensors, tactical response robot

1. Background

From a navigational perspective, the type of control strategy employed on a mobile platform runs the full spectrum defined by teleoperated at the low end through fully autonomous at the upper extreme. A teleoperated machine of the lowest order has no onboard intelligence and blindly executes the drive and steering commands sent down in real-time by a remote operator. A fully autonomous mobile platform, on the other hand, keeps track of its position and orientation and typically uses some type of world modeling scheme to represent the location of perceived objects in its surroundings. A very common approach is to employ a statistical certainty-grid representation (Moravec and Elfes, 1985), where each cell in the grid corresponds to a particular "unit square" of floor space. The numerical value assigned to each cell represents the probability that its associated location in the building is occupied by some object, with a value of zero indicating free space (i.e., no obstacles present).

The existence of an absolute world model allows for automatic path planning, and subsequent route revisions in the event a new obstacle is encountered. Unfortunately, however, the autonomous execution of indoor paths generally requires a priori knowledge of the floorplan of the operating environment, and in all cases the robot must maintain an accurate awareness of its position and orientation. Accordingly, traditional autonomous navigation techniques (Borenstein et al., 1996) have until recently been of limited utility for applications where a requirement exists to enter previously unexplored structures of opportunity as the need arises. (More recent efforts have begun to make some noteworthy progress in this arena, as reported by Gutmann and Konolidge (2000) and Thrun et al. (2000), for example.)

Teleoperated systems, on the other hand, permit remote operation in such unknown environments, but conventionally place unacceptable demands on the operator. Simply driving a teleoperated platform using vehicle-based video feedback is no trivial matter, and can be stressful and fatiguing even under very favorable conditions (Aviles et al., 1990). If a remote operator has to master simultaneous inputs for drive, steering, camera, and weapons control, the chances of successfully performing coordinated actions in a timely fashion are minimal.

*http://www.spawar.navy.mil/robots/

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2001**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **An Advanced Telereflexive Tactical Response Robot**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **H. R. /Everett; G. A. /Gilbreath; D. A. /Ciccimaro**	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Space and Naval Warfare Systems Center 53406 Woodward Road San Diego, CA 92152**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Easing the driving burden on the operator was a major force behind the development of the reflexive teleoperated control scheme employed on ROBART II (Everett et al., 1990; Laird and Everett, 1990), a prototype security robot capable of both teleoperated and autonomous operation. The robot's numerous collision-avoidance sensors, originally intended to provide an envelope of protection during autonomous transit, were also called into play during manual operation to greatly minimize the possibility of operator error. The commanded velocity and direction of the platform was altered by the onboard processors to keep the robot traveling at a safe speed and preclude running into obstructions. Work on ROBART III (Fig. 1) now extends this reflexive-teleoperation concept into the realm of sensor-assisted camera and weapon control for indoor tactical systems.

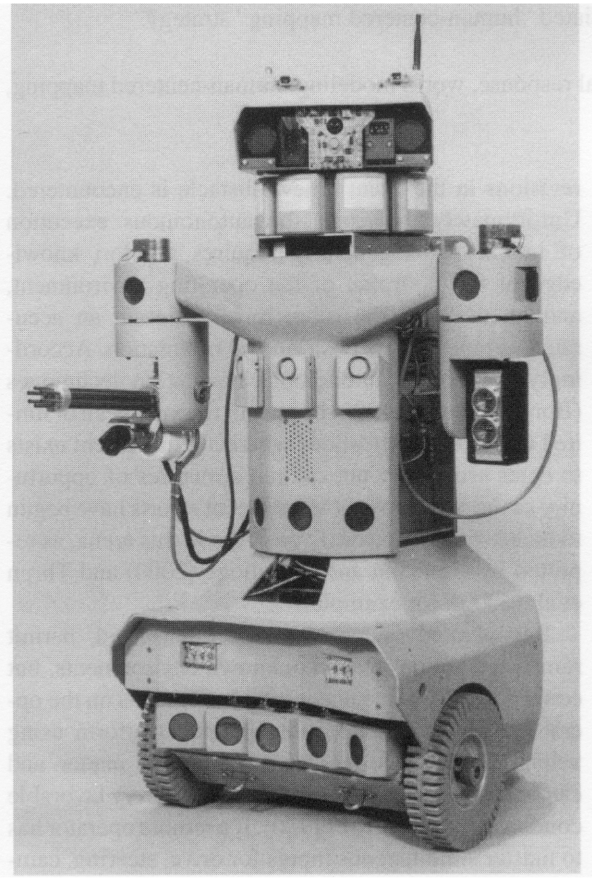


Figure 1. ROBART **III** is a laboratory prototype supporting the development of enhanced telereflection control strategies for tactical response robots.

2. Man-Machine Interface

A very simplistic graphical user interface (GUI) has been implemented under Visual Basic to support the development and diagnostic needs of this technology-base effort (Fig. 2). For purposes of this discussion, the man-machine interface issues can be subdivided into three general categories: 1) mobility control, 2) camera control, and 3) non-lethal weapon control.

2.1. Mobility Control

The *Mobility Control Window* (lower right corner of the screen) provides a convenient means for the operator to set the desired speed, and if necessary, manually change the platform's heading. Each time the operator clicks on the forward arrow button (lower-right corner of Fig. 2), for example, the platform's velocity is increased one increment. Clicking on either the right- or left-turn arrows imposes a differential turn on the forward velocity, speeding up one wheel and slowing down the other. The more times a turn arrow is clicked, the bigger the differential and hence the faster the rate of turn. If the forward (or reverse) speed is zero (i.e., platform stopped), clicking a turn button causes the robot to pivot in place.

Once the platform is set in motion, the operator can easily control its subsequent actions by clicking on special behavioral icons depicted on the navigation display. For example, selecting a *wall-following* icon causes the platform to enter wall-following mode, maintaining its current lateral offset from the indicated wall using side-looking sonar. The *wall-following* icons are implemented as long vertical command buttons situated on either side of the *Map Window* in the lower left corner. The nine dots displayed in front of the rectangular robot icon at the bottom of the map indicate the measured range to perceived objects in the path.

Two additional wall-segment icons are seen above the map in the form of short-length horizontal command buttons. The open spaces between these graphical depictions of wall structures represent three potential *doorways:* one directly ahead of the robot and one on either side. By clicking in one of these *doorway icons,* the robot is instructed to seek out and enter the next encountered location of that type of door along its current path. For the example illustrated Fig. 2, the platform is looking for a door off to the left, as indicated by the highlight box shown in the selected *doorway icon,*

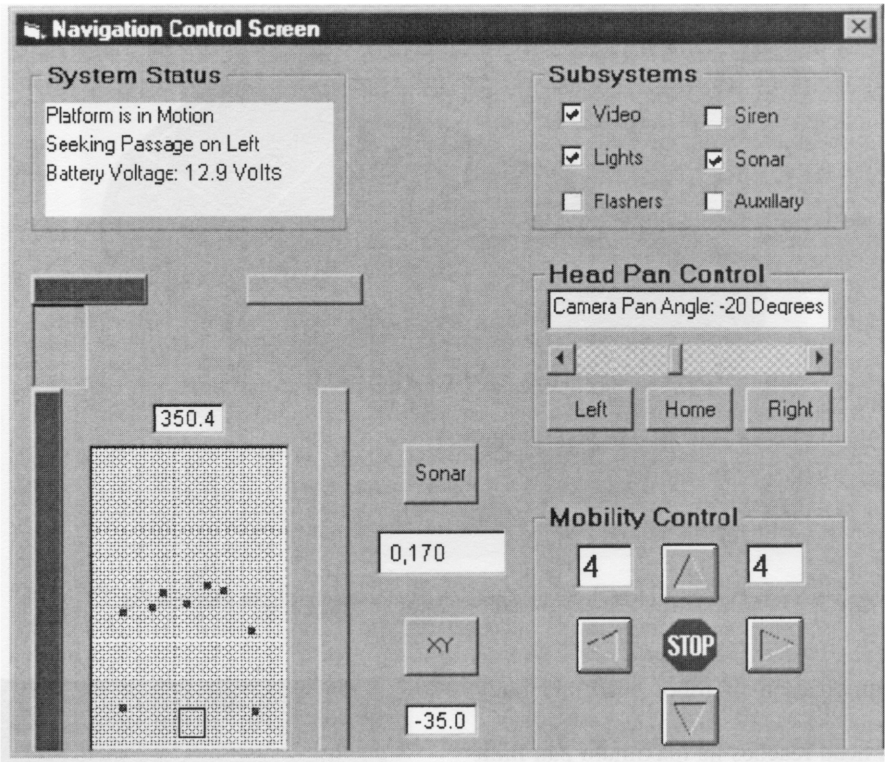


Figure 2. Navigation Control Screen, showing the high-level driving icons surrounding the *Map Window* (lower left corner). The robot has been instructed to enter the next door encountered on the left.

and the associated text displayed in the *System Status Window* above the map.

The primary mobility controls shown Fig. 2 are mimicked on a stand-alone hand-held pendent (Fig. 3) employing an array of capacitive touch-sensor icons, based on the Quantum Research ***QProx*** *E6S2* matrix decoder. A high-resolution 2.5-inch color LCD monitor provides video output, in addition to selected status information overlaid at the top of the screen. A miniature motor-driven eccentric (as found in vibrating pagers) is mounted inside the enclosure to provide tactile motion feedback to the user (Everett and Nieusma, 1994). The speed of this motor (and hence the vibration of the case) is varied in direct proportion to the velocity of the remote platform.

2.2. *Camera Control*

Manual control of the ROBART'S head-mounted camera can be accomplished using the slider and button controls within the *Head Pan Control Window* on the right side of the display screen. In addition, computer-aided camera pan is provided to support the three system functionalities of platform mobility, intruder assessment, and weapon tracking. For mobility, the camera-pan commands are embedded within the "seek-door" behaviors. If the robot is instructed to enter the next door on the right, for example, the camera immediately turns 45 degrees right of center to acknowledge the behavior request and provide a better view of the doorway detection process. As soon as the door is detected and the penetration behavior invoked, the camera pans to compensate for the platform's rate of turn in order to keep the door opening in the center of its field-of-view.

The intruder detection and assessment algorithms operate upon the output from the video motion detection (VMD) system and a 360-degree array of passive-infrared (PIR) sensors configured as a collar just below the head. The PIR data is used to pan the surveillance camera to the center of any zone with suspected intruder activity. The VMD output is then used to track and keep the intruder in the center of the visual

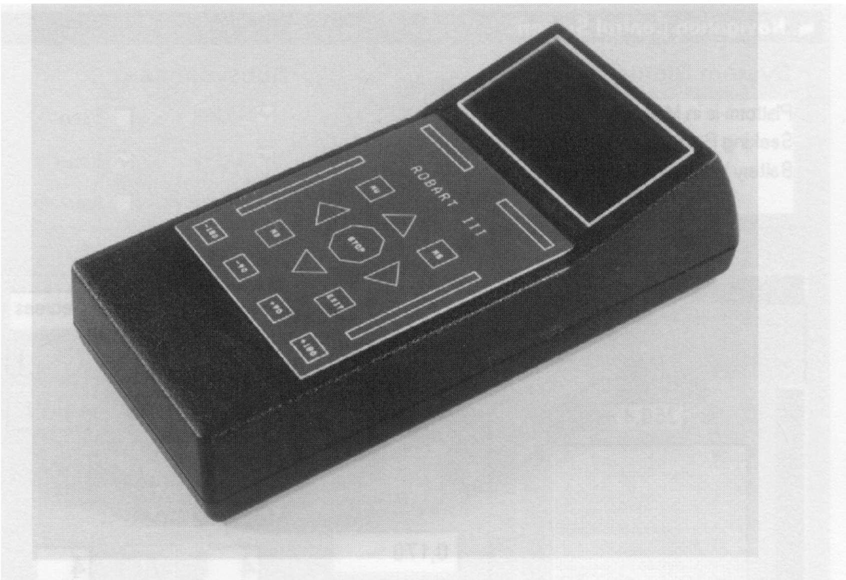


Figure 3. A capacitive touch-panel interface on the hand-held pendent mimics the drive icons shown in Fig. 2.

field, using a combination of robot head and body movement.

Whenever the head reaches its maximum pan limit (+/-100 degrees) relative to the robot, the mobility base will pivot in place towards the target. The head meanwhile moves at the same speed in the opposite direction to keep the primary target in the center of the visual field. This coordinated action provides the robot with unlimited (i.e., continuous 360-degree) pan coverage.

Automated camera pan for weapon tracking is treated in the next section.

2.3. Non-Lethal Weapon Control

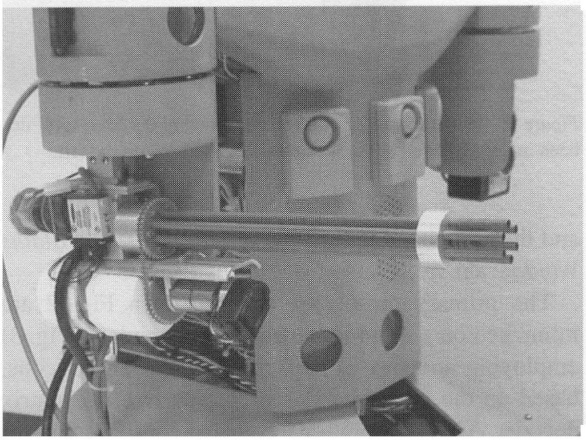


Figure 4. A six-barrel pneumatic tranquilizer gun is used to demonstrate computer-assisted control of a non-lethal weapon.

The principle non-lethal response system incorporated on ROBART III is a six-barreled pneumatically-powered Gatling-gun (Fig. 4) capable of firing 3/16-inch-diameter simulated tranquilizer darts or plastic bullets. Projectiles are expelled at a high velocity from 12-inch barrels by a release of compressed air from a pressurized accumulator at the rear of the gun assembly. The main air bottle is automatically recharged by a small 12-volt reciprocating compressor mounted in the robot's base.

The operator specifies what type of control strategy (i.e., manual or automatic) to use when entering weapon-tracking mode by clicking on the appropriate option in the *TrackMode Window* (bottom-right corner of Fig. 5). In manual mode, the firing decision is made by the operator. A 5-milliwatt 670-nanometer visible-red laser sight facilitates manual training of the weapon using video from the head-mounted surveillance camera. The operator can slave the surveillance camera to the weapon pan axis by clicking on the "Head" option in the *Slave Window* (just below the *System Status Window*, upper left corner). The mobility base can also be slaved, so the robot turns to face the direction the weapon is aimed. If a forward drive speed is entered at this point, the operator merely has to keep the weapon

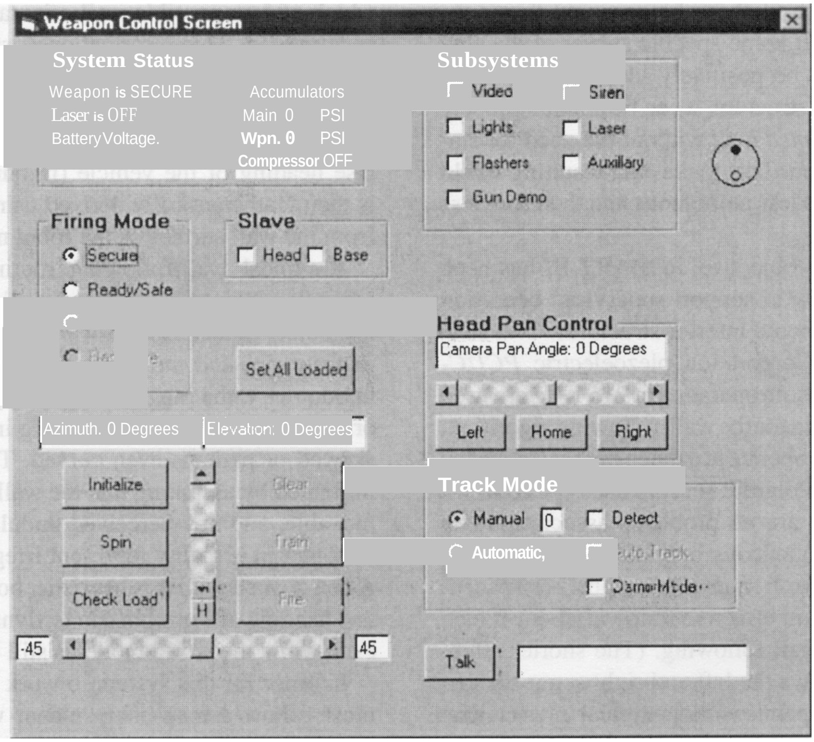


Figure 5. Interim control and diagnostic screen used during development of the computer-assisted-weapon-control software on ROBART III.

trained on the intruder for the robot to automatically give chase.

In automatic mode, ROBART III is responsible for making the firing decision, contingent upon a confirmed target solution stabilized for a pre-determined time interval, and pre-authorization from the operator. Azimuthal and elevation information from the VMD is available to the right-shoulder pan-and-tilt controller for purposes of automated weapon positioning. When *weapon-tracking* is activated in automatic mode, the robot centers its head and turns to face toward the current threat. The mobility base then becomes stationary while the weapon begins tracking the target.

3. Human-Centered Mapping

The exploration and mapping of unknown structures benefits significantly when the interpretation of raw sensor data is augmented by simultaneous supervisory input from the human operator. A *human-centered mapping* strategy has been developed to ensure valid first-time interpretation of navigational landmarks as the robot builds its world model (currently on an external RF-linked desktop PC). In a nutshell, the robot can enter and explore an unknown space, building a valid model representation on the fly, while dynamically re-referencing itself in the process to null out accumulated dead-reckoning errors.

Upon first entering a previously unexplored building, the operator guides the robot using typical commands like: “follow the wall on your left,” and “enter the next doorway on the left.” Such high-level direction is provided by clicking on screen icons, as previously described. In addition to directing the robot’s immediate behavior, however, these same commands also provide valuable information to the world-modeling algorithm. The ambiguity of interpreting statistical data for the purpose of classifying certain environmental attributes (i.e., walls and doorways, in this example) is completely eliminated. The end result of such an approach is a much faster and more accurate generation of object representations (relative to conventional sensor-only data collections), particularly valuable when there is no a priori information available to the system.

The world model is first initialized as a two-dimensional dynamic array with all cells marked as *unknown*. (An *unknown* cell is treated as potentially

traversable, but more likely to be occupied than confirmed *free space*.) If some specific subset of the current sonar data can be positively identified from the outset as a wall-like structure, it can be unambiguously modeled as a *confirmed wall* without the need for statistical representation. This makes the resulting world representation much less ambiguous and therefore less subject to error.

In support of this objective, ROBART III has been equipped specifically to support supervised operation in previously unexplored interior structures. Two self-contained Electro Corporation piezoelectric *PCUC-series* ultrasonic sensors operating at 215 KHz are used to generate range data for the wall-following algorithm. These sonar sensors operate at a much higher frequency than the **49.4-KHz** Polaroid sensors used for collision avoidance, so there are no problems associated with crosstalk from simultaneous operation of both types. In addition, the higher frequencies support better accuracy with a maximum effective range of about 6 feet, which is ideal for wall following. (The shorter effective range limit allows the left and right sonar sensors to asynchronously operate without mutual interference, for a faster update rate).

4. Orthogonal Navigation

The Achilles Heel of any world-modeling scheme, however, is accurate positional referencing in real-time by the moving platform. Since all sensor data is taken relative to the robot's location and orientation, the accuracy (and usefulness) of the model quickly degrades as the robot becomes disoriented. While wall following is a very powerful tool in and of itself for determining the relative offset and heading of the robot, conventional schemes normally assume some a priori information about the wall in the first place to facilitate its utility as a navigational reference. In short, a relative fix with respect to an unknown entity does not yield an unambiguous absolute solution, for obvious reasons.

ROBART III uses a world modeling technique that requires no such a priori information. This navigation scheme, called *orthogonal navigation,* or *"Ortho-Nav,"* exploits the orthogonal nature of most building structures where walls are parallel and connecting hallways and doors are orthogonal. *Ortho-Nav* also uses the input from a magnetic compass to address the issue of absolute wall orientation. The accuracy of the compass need be only good enough to resolve the ambiguity of which of four possible wall orientations the robot has encountered. This information is stored in the model in conjunction with the wall representation (i.e., wall segment running north-south, or wall segment running east-west), in arbitrary building coordinates. The precise heading of the vehicle (in building coordinates) is then mathematically derived using sonar data taken from the wall surface as the robot moves.

A typical wall-following routine uses a ranging sensor to maintain a particular distance from a planar object (wall) on one or both sides. Due to sensor inaccuracies and the accumulation of errors inherent in odometry, the range data will appear to drift toward or away from the robot, resulting in a wall plot that is skewed or perhaps even curved. These errors can be mitigated by assuming that the wall is straight and immovable, and any perceived undulations in the sonar data plot in actuality represent irregular motion of the robot. Armed with this heuristic, both the lateral offset and heading of the robot can be dynamically corrected, even while the world model is still being generated.

In order for this system to work properly, the robot must follow a reasonably planar wall surface rather than just blindly reacting to whatever clutter is nearby. This is where the *human-centered* aspect of the scheme comes into play. By way of example, when the robot enters an unknown space under telereflexive control as illustrated in Fig. 6, the operator examines the video and informs the robot there is a wall it can follow on the left side. In addition, the operator also clicks on the *left doorway* icon (as illustrated earlier in Fig. 2) to further instruct the robot to find and enter the next doorway on the left. The onboard computer then begins acquiring range data from the appropriate sensors. When enough points have been accumulated for a fit (subject to a quality-of-fit-criteria), the resulting line is examined to determine its orientation.

The majority of buildings are laid out such that all walls are either parallel or orthogonal to one another, so the orientation of the line is snapped to 0, 90°, 180°, or 270° in arbitrary building coordinates. The robot's heading is then reset to this same value. Once the initial location of the wall has been established, an infinitely long *potential-wall* representation is entered into the model (Fig. 7).

As the robot continues to follow the actual wall getting valid line fits, it incrementally converts the *potential wall* to a *confirmed wall.*

As previously discussed, the robot can now correct its lateral position by using the wall as a reference. For

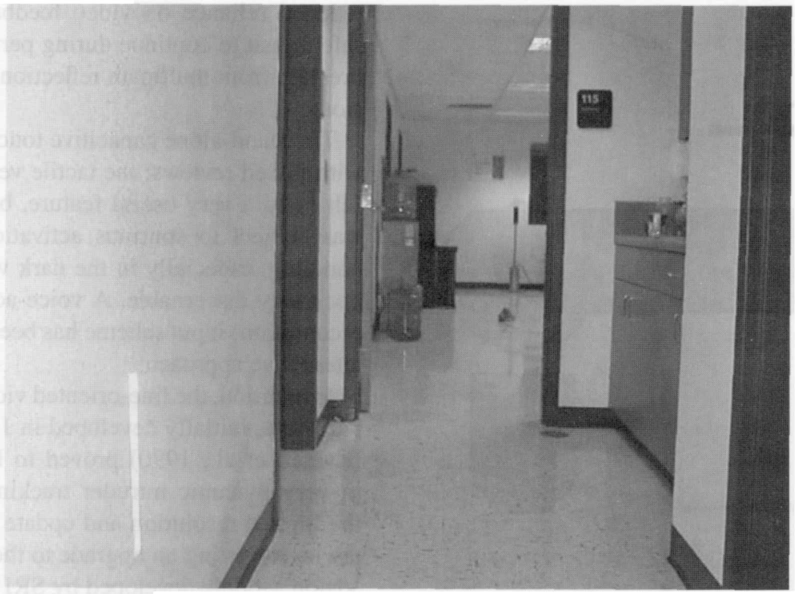


Figure 6. Initial view of an interior space as seen from the robot's onboard surveillance camera, revealing **a** clean wall for following on the immediate left.

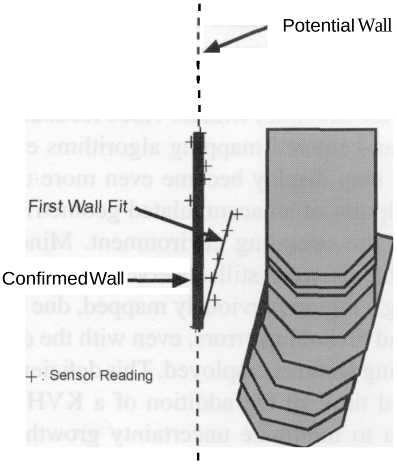


Figure 7. After obtaining the first wall fit, a potential wall is created and indexed to the cardinal heading which most closely matches the magnetic compass reading.

the situation shown above, given that the X coordinate of the wall is W_x and the current range to the wall is r, the robot's X coordinate is given by $R_x = W_x + r$. Similarly, the robot's current heading can be dynamically corrected by subtracting the difference between the orientation of the current wall fit and the current wall orientation from the robot's current heading. This is given by the following equation:

$$R_\theta = R_\theta - (F_\theta - W_\theta)$$

where:

R_θ = the robot's current heading
F_θ = the orientation of the current wall fit
W_θ = the orientation of the current wall

The robot turns left (as previously instructed) to enter the discovered doorway, using the ranging sensors on both sides to determine the size of the opening that must be cut in the wall it has been constructing (Fig. S), to form the *doorway* representation. After transitting the doorway, the robot next detects and begins to follow a wall to its right. Accordingly, it constructs a new potential wall and snaps it perpendicular to the previous model entry. Note this second *potential wall* (shown horizontally) is semi-infinite, in that it is clipped against the previously constructed *potential wall* (shown vertically).

Whenever the robot detects a new *potential wall*, it compares it to the list of *potential* and *confirmed walls* already constructed. If the new wall coincides (within pre-specified orientation and offset tolerances) with a

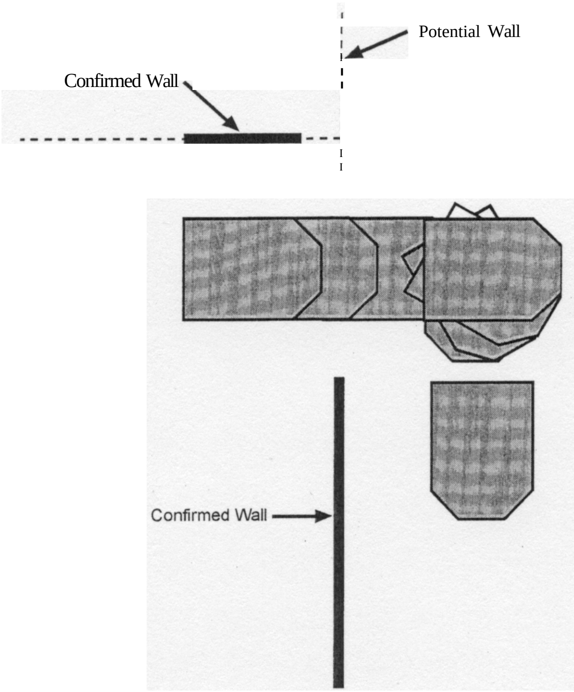


Figure 8. **As** the robot enters the found doorway, the modeling algorithm uses the side-sonar range information to cut **an** appropriately-sized opening through **the** existing (shown vertical) ***confirmed-*** and *potential-wall* representations. The new (horizontal) *potential wall* is clipped against the previously constructed *potential wall.*

previously modeled wall, the range data is snapped to the existing representation, rather than generating a new one.

5. Experimental Results

ROBART III has been operational in reflexive teleoperation mode since 1997, supporting extensive testing and evaluation of the high-level drive control interface by a variety of skilled and unskilled users. The resulting feedback has significantly influenced subsequent upgrades to both hardware (i.e., the type and placement of collision avoidance sensors) and software (i.e., the layout and functionality of icons in the drive control window).

The consensus of all parties involved was very positive with respect to the effectiveness of the user-friendly interface, which allowed even first-time operators to achieve within minutes a degree of proficiency that would otherwise take weeks or even months to realize. **A** very common observation was the significantly reduced reliance on video feedback, which allowed safe transit to continue during periods of severe video breakup from multipath reflection or RF signal occlusion.

The stand-alone capacitive touch panel (Fig. 3) met with mixed reviews; the tactile velocity feedback was felt to be a very useful feature, but the input scheme was subject to spurious activation through careless handling, especially in the dark when the icons were not easily discernable. A voice-activated (i.e., speech recognition) input scheme has been briefly tested as an alternative approach.

In addition, the line-oriented video motion detection hardware, initially developed in 1988 for ROBART II (Everett et al., 1990) proved to be fairly inadequate in very dynamic intruder tracking scenarios, due to the limited resolution and update rate. Current efforts are investigating an upgrade to the stereoscopic Small Vision Module developed by SRI (Konolidge, 1997).

More recent testing (i.e., within the last two years) has addressed the effectiveness of the human-centered mapping scheme. The most noticeable improvement early on was availability of the real-time snapshot sonar plots (Fig. 2) to augment forward-area perception by the operator during video dropouts. With a little practice, experienced operators were able to execute simple missions (i.e., traverse hallway and enter third doorway on right, for example) with no video feedback at all. **As** the human-centered mapping algorithms evolved, the resultant map display became even more useful from the standpoint of an accumulated geometric representation of the operating environment. Minor registration problems were still observed when circuitously revisiting a region previously mapped, due to accumulated dead reckoning errors, even with the dynamic re-referencing features employed. This deficiency is being addressed through the addition of a KVH fiber-optic rate gyro to minimize uncertainty growth in vehicle heading (Chung et al., 2000).

6. Conclusion

Much noteworthy progress has recently been made with regard to navigating without a priori map information, particularly under the **DARPA** Tactical Mobile Robot program (Krotkov and Blitch, 1999). But for the most part, little has been done to simplify the coordinated control of platform motion and any associated application payload from the operator's perspective. This paper covers the implementation of a prototype

tactical/security response robot capable of supervised-autonomous exploration in unknown structures. The system is able to confront intruders with a laser-sighted tranquilizer dart gun, and automatically track a moving target with the use of various sensors. A *human-centered mapping* scheme ensures more accurate first-time interpretation of navigational landmarks as the robot builds its world model, while *orthogonal navigation* exploits the fact that the majority of man-made structures are characterized by parallel and orthogonal walls.

References

Aviles, W.A., Hughes, T.W., Everett, H.R., Umeda, A.Y., Martin, S.W., Koyamatsu, A.H., Solorzano, M.R., Laird, R.T., and McArthur, S.P. 1990. Issues in mobile robotics: The unmanned ground vehicle program teleoperated vehicle. *SPIE Mobile Robots V,* Boston, MA, pp. 587–597.

Borenstein, J., Everett, H.R., and Feng, L. 1996. *Navigating Mobile Robots: Systems und Techniques,* A.K. Peters Ltd.: Wellesley, MA.

Chung, H., Ojedo, L., and Borenstein, J. 2000. Accurate mobile robot dead-reckoning with a precision calibrated fiber optic gyro. *IEEE International Conference for Robotics and Automation,* San Francisco, CA.

Everett, H.R., Gilbreath, G.A., Tran, T., and Nieusma, J.M. 1990. Modeling the Environment of a Mobile Security Robot. Technical Document 1835, Naval Ocean Systems Canter, San Diego, CA.

Everett, H.R. and Nieusma, J.M. 1994. Feedback System for Remotely Operated Vehicles, Navy Case No. 73322, **U.S.** Patent No. 5,309,140.

Gutmann, J.-S. and Konolige, K. 2000. Incremental mapping of large cyclic environments. *CIRA*.

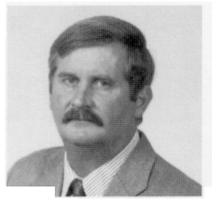
Konolidge, K. 1997. Small vision systems: Hardware and implementation. *Eighth International Symposium on Robotics Research,* Hayama, Japan.

Krotkov, E. and Blitch, J. 1999. The defense advanced research projects agency (DARPA) tactical mobile robotics program. *International Journal of Robotics Research,* 18(7):769-776.

Laird, R.T. and Everett, H.R. 1990. Reflexive teleoperated control. Association for unmanned vehicle systems. *17th Annual Technical Symposium and Exhibition (AUVS '90),* Dayton, OH, pp. 280-292.

Moravec, H.P. and Elfes, A. 1985. High resolution maps from wide angle sonar. In *Proceedings of the 1985 IEEE International Conference on Robotics and Automation,* St. Louis, MO, pp. 116-121.

Thrun, **S.,** Fox, D., Burgard, W., and Dellaert, F. 2000. Robust Monte Carlo localization for mobile robots. Carnegie Mellon University, Pittsburgh, PA, CMU-CS-00-125.



Commander H.R. (Bart) Everett USN (Ret.) is the former Director of the Office of Robotics and Autonomous Systems at the Naval Sea Systems Command, Washington, DC. He currently serves as Associate Division Head for Robotics at the Space and Naval Warfare Systems Center, San Diego, and as the Technical Director of the Mobile Detection Assessment Response System (MDARS) project. Active in the field of mobile robotics research since 1965, with personal involvement in the development of 14 mobile systems, he has over 80 technical publications and 19 related patents issued or pending. He serves on the editorial board of "Robotics and Autonomous Systems" magazine, and is a member of Sigma Xi, the Institute of Electrical and Electronics Engineers, and the Association for Unmanned Vehicle Systems International.

Gary Gilbreath received his undergraduate degree in electrical engineering from the University of California in San Diego, CA. He has previously served as Lead Software Engineer for the ROBART II Independent Exploratory Development program, and currently serves as Program Manager at SPAWAR Systems Center, San Diego for the Mobile Detection Assessment Response System (MDARS) Interior program. He holds X patents and has published X technical papers on robotics related technology.

Donny Ciccimaro received his BS and MS degrees in electrical engineering from Florida State University. He has previously served as engineer on ROBART **III**, an Automated Security Response Robot, and Man Portable Robotic System (MPRS).